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Haemodynamic Properties of PTFE Femoropopliteal Bypass Grafts as Determined by a New Magnetic Resonance Technique

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Objectives. *To apply the automatic three dimensional paraboloid (3DP) method for measurement of wall shear stress (WSS), blood flow, blood velocity, and cross sectional graft lumen area to magnetic resonance phase contrast velocity mapping data acquired from polytetrafluoroethylene (PTFE) suprageniculate 6 mm femoropopliteal bypass grafts to determine the biomechanical and haemodynamic properties immediately and three years after implantation.*
Materials and methods. *Two patient cohorts, each of ten patients, with intermittent claudication were investigated by the 3DP method, one group (A) within 36 h after implantation of a femoropopliteal graft and the other group (B) 35 months after implantation.*
Results. *The mean blood flow was 5.9 ml/s (SD: 1.6), and WSS at peak systole was 2.2 N/m^2 (SD: 0.6) 5 cm upstream to the distal anastomosis for group A, and 3.7 ml/s (SD: 1.9) and 1.9 N/m^2 (SD: 0.4) for Group B. The WSS varied according to the angular position of the graft circumference. The implanted grafts were not circular but had a slightly elliptical circumference with a greater anterior/posterior diameter.*
Conclusion. *The 3DP method is a precise tool with subpixel resolution for determining the biomechanical and haemodynamic properties of implanted PTFE grafts, and it can be used to assess graft function immediately after implantation. It is potentially applicable for routine graft surveillance.*

Key Words: Biomechanics; Blood vessel prosthesis; Haemodynamics; Magnetic resonance; PTFE.

Introduction

Synthetic arterial grafts were implanted in the suprageniculate femoropopliteal position with a frequency of four per 100.000 inhabitants (all ages) in the year 2000 in Denmark (Danish Vascular Registry 2000; Internet website http://www.karbase.dk). The effect of structured, postoperative surveillance programmes with conventional ultrasound sonography is controversial since it is not clear whether ultrasound technology is helpful to reliably detect failing femoropopliteal prosthetic grafts,[1–6] and in addition there is considerable interobserver variability in duplex scanning.[7] The physical properties of the most widely used grafts in this position, polytetrafluoroethylene (PTFE) prostheses,[8] make it difficult, if not impossible, to obtain adequate acoustic penetration of the initially air filled interstices in the microporous node-fibril structure of the PTFE material.

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Due to the lack of appropriate non invasive techniques, the biomechanical and haemodynamic properties of these grafts after implantation are poorly documented in the literature. The present study was undertaken to study these vascular grafts non invasively and in vivo by using magnetic resonance (MR) phase contrast velocity mapping techniques with high temporal and spatial resolution and subject the acquired data to post processing analysis employing the new automatic three dimensional paraboloid (3DP) method for determination of blood flow velocity, volume blood flow, cross sectional graft lumen area, and wall shear stress (WSS) based on subpixel edge detection.[9]

Material and Methods

Two groups of patients were examined: (A) Ten patients (median age 63 years; range 52–80; two women) with intermittent claudication[10] due to occlusion of the superficial femoral artery were studied by

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MR techniques within 36 h after implantation of a PTFE Atrium® tube prosthesis (factory specified diameter 6 mm) in the suprageniculate femoropopliteal position. (B) Ten patients (median age 69 years; range 62–78; three women) with the same indication and surgical technique were studied at a median of 35 months (range 17–67) after implantation of a 6 mm PTFE (GoreTex Stretch®) bypass all with a non-assisted primary patency. The protocol was approved by the local ethical committee, and individually signed informed consent forms were obtained according to the Helsinki II declaration.

In all cases, the examinations were performed using a Philips Gyroscan NT 1.5 T MR scanner with 21 mT/m, 105 mT/m/ms gradient system. To optimise the signal to noise ratio, a standard 8 cm diameter surface coil was positioned above the distal anastomosis of the graft. After initial visualisation of morphology by sagittal, transversal, and coronal scout images, perpendicular blood flow velocity measurements were made 5 cm upstream of the distal anastomosis to avoid the disturbed flow known to occur in the anastomoses regions. A standard, retrospectively electrocardiogram gated velocity encoded gradient echo sequence was used with the following settings: Thirty-two frames were recorded throughout the cycle with an interval of 25 ms starting from the R-wave. The slice thickness was 6 mm, and in-plane pixel resolution was $0.5 \times 0.5\ mm^2$ (data acquisition 128×128 matrix, 64 mm field of view). Two signal averages and a maximum velocity sensitivity of ± 100 cm/s were used.

Phase correction was applied to all data sets. A visual identification of the graft was made, and a square region of interest was manually selected in the images acquired at the time where peak flow was identified; these were the only user dependent interactions.

The cross sectional lumen area of the graft, quantification of the blood flow, and the WSS were determined at peak systole using the automatic 3DP fitting technique.[9,11–14]

Wall shear rate was determined in each of 24 sectors 90° wide located equidistantly along the circumference of the graft. Sector layers, each of 0.1 mm, was placed in 11 equidistant radial positions in each of these 24 sectors, and the maximum wall shear rate value within each of the 11 layers was automatically chosen as the wall shear rate value for that sector. The wall shear rates were transformed into WSS by multiplication with the dynamic viscosity of the blood. Data from all sector layers in each radial position were fitted to the user independent 3DP model. Assuming that the cross sectional graft lumen area cannot be underestimated, the series with the smallest area was selected automatically as the true graft area.[15] The elliptic component was then calculated from the internal graft radius at two points of the circumference perpendicular to each other. Blood flow rate was calculated from the data of the entire heart cycle.

Statistics. The 3DP model (multiple linear regression) statistics used were the root mean square error (RMSE) and the adjusted r^2 which were automatically converted into standard errors of the two measured variables, area and WSS. Paired *t*-tests were used as appropriate after testing for normal distribution using a probability plot.

Results

A normal MR modulus image in a cross sectional plane (a transectional scout image) of the blood flow in a typical 6 mm tube graft inserted in the suprageniculate femoropopliteal position with $0.5 \times 0.5\ mm^2$ pixel resolution is presented in Fig. 1(A). The corresponding blood flow velocity image (phase velocity image) is presented in Fig. 1(B).

The blood flow rate as a function of time determined throughout the cardiac cycle in similar graft from one single patient is illustrated in Fig. 2. It is seen that the blood flow is directed distally for most parts of the cycle except 390–460 ms after the maximum of the R-wave i.e. the diastolic retrograde blood flow was minimal in this case. When the blood flow is integrated throughout the cycle, the total volume blood flow can be assessed for that cycle and/or converted to graft volume blood flow per ml/s or ml/min as requested.

Fig. 3 presents the localisation of the graft wall as determined by the 3DP method. It is seen that the position of the graft wall (the circumferential edge detection by the 3DP method) is very precise with subpixel positioning. Note the slight, but clearly visible, elliptic form of the implanted graft with a greater anterior/posterior diameter than the right/left diameter. The arrow to the right in the plot indicates the position corresponding to the arrow to the left in the plot of Fig. 4.

In Fig. 4, the WSS at peak systole in each of the 24 sectors as determined by the 3DP method throughout the circumference of the PTFE graft is plotted as a function of the angular position throughout the graft circumference. The arrow to the left of the plot indicates the circumferential position corresponding to the arrow in Fig. 4. The graph shows that the WSS varies considerably along the graft circumference and visualises the heterogeneity of the frictional forces acting on the inner side of a femoropopliteal PTFE graft.

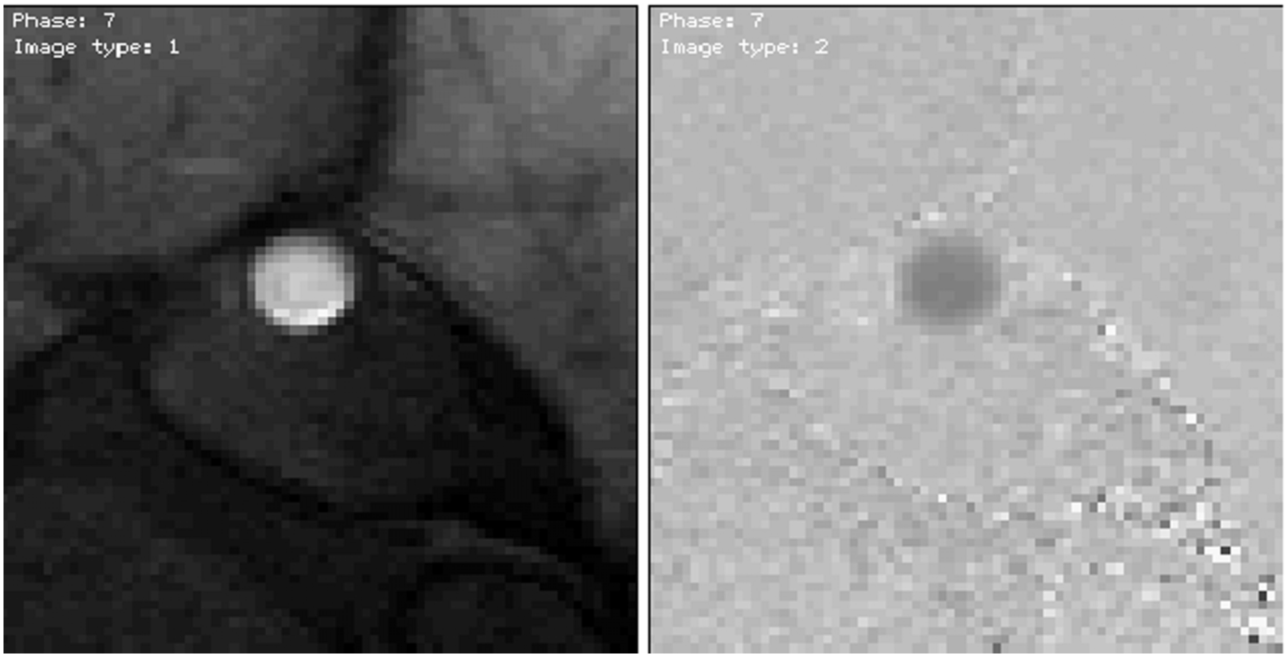

Fig. 1. (A) The transectional modulus image of the blood flow in a 6 mm PTFE graft implanted at the femoropopliteal level obtained 5 cm upstream to the distal suprageniculate anastomosis (0.5×0.5 mm^2 pixel resolution). (B) The phase velocity image corresponding to A.

The data sets are presented in Tables 1(a) and (b). For all patients sufficient data sets were acquired from peak systole in all 24 sectors. The statistical variables for the 3DP method indicate the quality of the data acquisition; the adjusted r^2 was 0.95 and 0.96 for groups A and B, respectively. The edge points were estimated with a mean methodological standard error of 44.0–46.3 μm—a subpixel precision as expected from the automatic 3DP method.

The mean graft area of 28.7 mm^2 corresponds to an internal graft diameter of 6.04 mm for the recently operated and the graft area of 28.6 mm^2 to a diameter of 6.03 mm for the long term group. Student's t-test did not show any significant difference between the

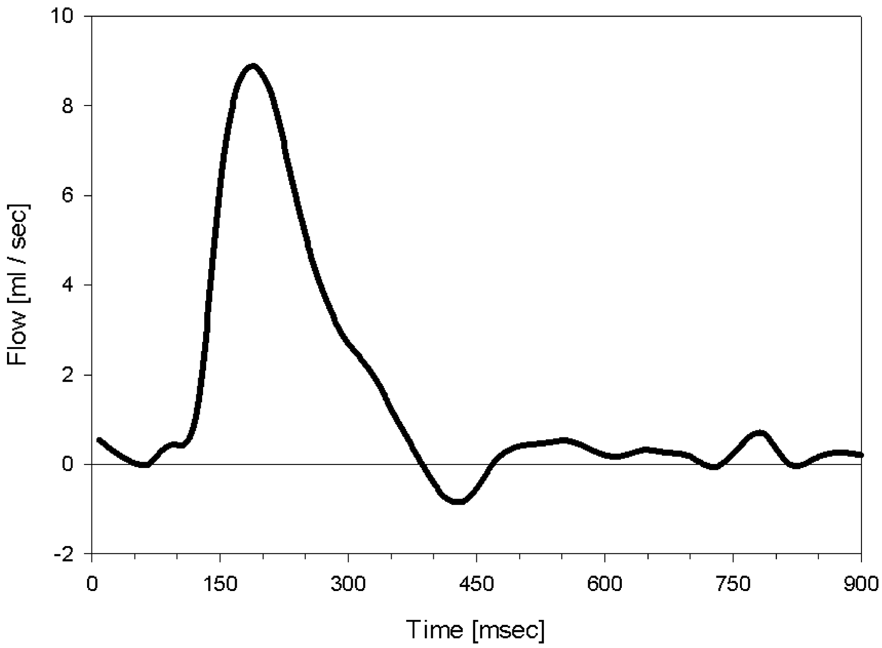

Fig. 2. The volume blood flow in the femoropopliteal PTFE bypass plotted as a function of time throughout the cardiac cycle.

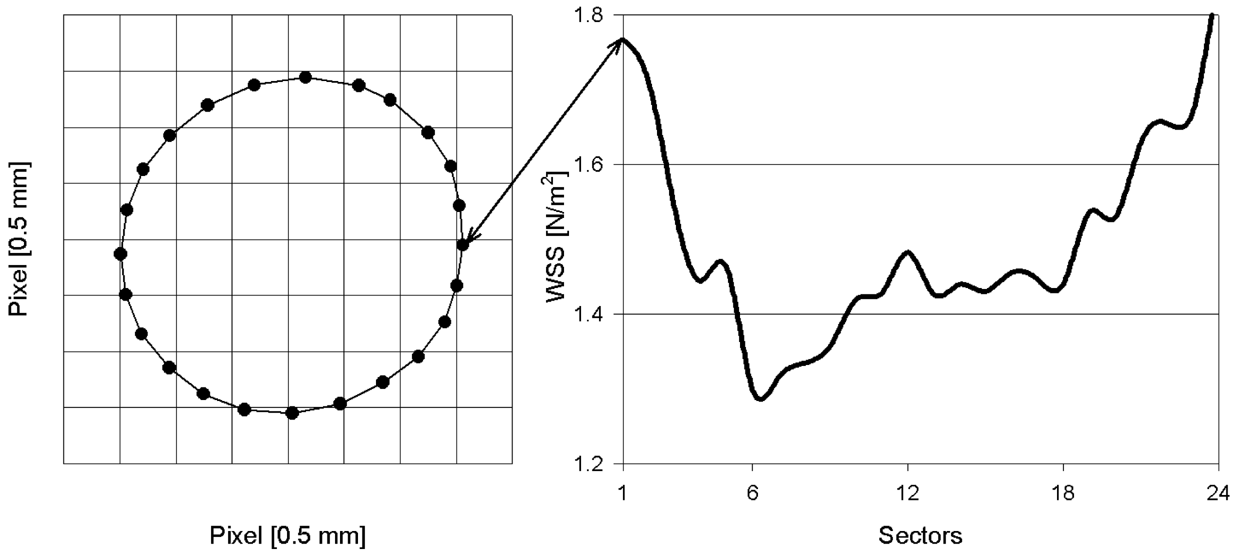

Fig. 3. The dots indicate the position of the circumference of the PTFE bypass in each of the 24 sectors. Note the subpixel resolution and the slightly elliptic shape of the circumference. The arrow indicates the same circumferential position as the arrow in Fig. 4.
Fig. 4. The wall shear stress at peak systolic blood flow in each of the 24 sectors of the circumference of the PTFE graft.

graft lumen areas of the two groups ($p = 0.48$). After implantation, the grafts did not maintain the circumference of a perfect circle; the elliptic component of each graft was calculated from (diameter a)/(diameter b) where diameter a was the minimum diameter identified by visual analysis and diameter b was the corresponding value for the largest diameter. The elliptic component varied from 1.01 to 1.07 in group A and from 1.06 to 1.14 in group B. The mean WSS at peak systolic blood flow velocity was 2.22 N/m^2 for group A and 1.9 N/m^2 for group B.

Discussion

The primary data acquired by the present MR techniques were blood flow velocity inside the synthetic graft as measured perpendicularly throughout the cardiac cycle within each of 32 frames separated by a temporal interval of 25 ms. These data were then postprocessed using the principles of the 3DP fitting technique where all data points within the boundary layer of the blood to vessel wall interface are used for the fit. The 3DP method has been extensively validated in vitro[9,13] as well as in vivo, and it has been applied previously to the anterior and posterior wall of the suprarenal and infrarenal aorta,[11] the common carotid artery,[9,12,13] and the carotid bifurcation.[14] The correlation between the automatic edge detection of the 3DP method and a conventional manual edge detection as applied to the carotid artery showed r^2 values of 0.81 and 0.99 ($p < 0.0001$ for both) for WSS/peak centre velocities and manually/automatically determined blood flows, respectively.[12] The in vitro studies[9] showed that the lumen area of a 8.00 ± 0.01 mm glass tube model could be assessed by this technique with a mean error of 0.6%.

In the present study, sufficient data sets were acquired from peak systole in each of the 24 evenly distributed sectors of the graft circumference to allow

Table 1a. The results of the measurements on Atrium PTFE grafts within 36 hours after insertion.

Pt No.	Graft area (mm^2)	WSS (N/m^2)	WSS SE (N/m^2)	Radial SE (mm)	Flow (ml/s)
1	29.82	1.765	0.663	0.068	3.183
2	26.80	1.978	0.072	0.035	4.002
3	28.42	3.332	0.172	0.046	7.575
4	30.05	2.608	0.128	0.048	5.168
5	28.51	2.808	0.104	0.037	5.952
6	29.65	1.564	0.096	0.062	7.468
7	28.56	1.448	0.051	0.031	7.870
8	28.14	2.909	0.095	0.033	7.357
9	26.79	2.064	0.101	0.043	5.295
10	29.74	1.706	0.061	0.037	6.081
Mean	28.65	2.218	0.154	0.044	5.995
SD	1.19	0.6493	0.182	0.012	1.602

The graft area in mm^2 was determined according to the 3DP method from the 24 sectors into which the graft circumference was divided. WSS signifies wall shear stress; the tabulated value is the mean value of the values obtained in each of the 24 sectors at peak systolic blood flow velocity. WSS SE gives the methodological standard error of the mean as calculated in accordance with the 3DP method for the individual values in the WSS column. Radial SE indicates the standard error of the mean of the (virtual) graft radius as determined from the aggregated area assessment using the 24 sector values. The graft bloodflow is presented in ml/s and in Table 1(b) the last column gives the time elapsed after implantation of the prosthesis.

Table 1b. On GoreTex PTFE grafts at a median of 36 months after implantation.

Pt No.	Graft area (mm^2)	WSS (N/m^2)	WSS SE (N/m^2)	Radial SE (mm)	Flow (ml/s)	Graft implantation time (months)
1	26.77	2.019	0.065	0.029	1.361	58
2	25.43	2.182	0.147	0.068	5.835	57
3	25.77	1.662	0.094	0.061	1.877	35
4	28.91	1.503	0.075	0.058	1.694	26
5	27.62	2.261	0.110	0.041	5.327	17
6	30.79	1.415	0.116	0.042	1.972	67
7	29.46	2.626	0.088	0.033	2.622	26
8	27.07	1.672	0.475	0.024	4.637	27
9	32.13	2.129	0.157	0.069	5.218	19
10	31.92	2.133	0.081	0.039	6.428	16
Mean	28.59	1.960	0.098	0.046	3.697	35
SD	2.45	0.383	0.035	0.016	1.966	19

Legends as for Table 1a.

application of the 3PD postprocessing. As expected, the MR techniques for acquisition of the primary data are not in any way invalidated by the physical and chemical properties of the implanted PTFE material. The simple position of a standard surface coil above the region of interest on the thigh ensured consistent optimisation of the signal to noise ratio allowing safe and reliable acquisition of the data sets. This means that the biomechanical and haemodynamic properties of PTFE femoropopliteal grafts can be studied from immediately after implantation to the end of their lifespan. There was no difference between the MR signal pick up from within the Atrium (hybrid) grafts and the GoreTex (node-fibril) grafts in spite of their different cross sectional and longitudinal wall structure.

The advantage of the automatic 3DP method is that it is user independent except for a visual identification of the graft on the MR image and the manual selection of a square region comprising the region of the graft cross section in the image acquired at the time where peak flow is present. The identification of the precise location of the graft wall position in itself is not dependent on any user interference but is completely automatic.[15] This means that these MR studies avoid the interobserver variability[7] inherent to the duplex ultrasound techniques.

The compliance of these PTFE grafts is very small,[16] around 1.2 per cent per mmHg $\times 10^{-2}$, so, as expected, differential detections of position changes under the various heart cycle phases were not demonstrable: For all practical purposes, the PTFE grafts behave as stiff tubes. It was, however, a new observation that the grafts—which are perfectly circular in their circumference when homogeneously pressurised—attained a slight elliptic component after implantation. This is probably due to the skewed flow profiles, but this is speculative and needs to be studied further, since it may have important implications for the understanding of the forces acting on the distal anastomoses and of the formation of neointimal hyperplasia in these locations. The elliptic component of the graft has obvious implications for the calculation of graft area (and thus volume blood flow within the graft) by ultrasound techniques. With the present 3DP method these imprecisions are entirely avoided, since the graft area is calculated from the position of the edge points in the 24 sectors and not a simple diameter. The edge points are themselves determined with subpixel precision, and the localisation of the points used for determination of the graft circumference has a methodological standard error of 45 μm which is negligible for all practical and analytical purposes. With this in mind, the internal mean diameters of the grafts as calculated from the graft lumen area determined by the 3DP method were 6.04 mm for Atrium and 6.03 mm for GoreTex i.e. these grafts maintain their factory specification diameter after implantation.

The WSS at peak systolic blood flow velocities exhibited a complex pattern with marked, but systematic, variations around the circumference, see Fig. 4. This pattern was present in all the grafts examined. The mean systolic shear stress values of around 2.2 and 2.0 N/m^2 for the two series were found 5 cm upstream to the distal anastomosis with the popliteal artery where pulsatile flow is fully developed. The flow fields become much more complex at the anastomosis, and the hypothesis of reduced levels of WSS as a facilitator of intimal thickening with ingrowth of a intimal hyperplastic pannus migrating from the suture line needs to be examined in future MR studies since the experimental results reported in the literature have been obtained with for example laser Doppler anemometry.[17,18] The exact nature of the graft inlet flow waveforms on the perianastomotic flow fields has been studied in extremely complex models,[19–21] but the analysis is, of course, dependent on the primarily acquired data; the present 3DP technique is potentially well suited to clarification of this problem where not only the frictional forces of the blood acting on the anastomosis but also the translation of the mechanical forces of the pulse wave from the graft to the native artery are of theoretical importance.[22–24] The systolic and mean shear rates as determined in femoropopliteal grafts by ultrasound techniques are reported to be 671 and 168, respectively, at flow rates of some 126 ml/min.[25]

In conclusion, this experimental study applied the automated 3DP postprocessing technology to primary blood flow velocity data obtained by standard MR techniques. The acquisition of the data took about 1 h, and the total time necessary for the entire analysis of the data from one patient took 30–45 min. The methodology can be relatively easy mastered, and, after a short learning phase that did not affect the results only the time spent, the analysis became routine. We conclude that this techniques can be used for routine determination of haemodynamic and biomechanical variables in patients with femoropopliteal PTFE grafts and thus provide data that might be useful for identifying failing grafts.

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